Element 4: Watershed Characteristics and Landscape Factors Influencing Vulnerability and Resilience to Rising Stream Temperatures

A. Contributors

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At-A-Glance

> Land cover and landscape features in a watershed can affect whether stream water temperatures fluctuate at a higher or lower rate than air temperatures. In general, forested landscapes moderate the impact of rising air/stream temperatures, while developed landscapes magnify that impact.
>
> Recent work has indicated that water temperatures may not be directly correlated with warming air temperatures, and groundwater influence during baseflows can strongly influence stream temperature by mitigating thermal impacts even during droughts (Briggs et al. 2018, Kanno et al. 2014, Snyder et al. 2015, Trumbo et al. 2014).
>
> Ideal modeling studies would integrate the effects of current and future land use, climate and weather extremes, and hydrologic response. These have not been developed, but are needed to understand best management practices for water temperature and where to apply them.
>
> Some studies include water temperature as an indicator of watershed health. But even without water temperature per se, future impacts of climate change, temperature, and other stressors depend on the resilience or health of the watershed and beneficial watershed features. Resilient watersheds can recover from temperature increases in their upper reaches.

B. Resources

Resources used in this overview include a mix of studies, models, and previously assessed information focused on hydrologic and anthropogenic activities and stressors that potentially impact water temperature. There is an abundance of literature, geo-spatial tools, and models to help articulate all the influencing landscape factors related to watershed health. To make this task manageable, available resources clearly linked to Chesapeake Bay issues will be used to give a characterization of the landscape and how the characteristics impact stream temperatures.

- The Chesapeake Bay Program's "Chesapeake Healthy Watershed Assessment" (CHWA) Chesapeake Healthy Watersheds Assessment (chesapeakebay.net) is a recent analysis using land cover and an array of watershed characteristics.
- The Maryland Department of Natural Resources publication "Land Use Characteristics of Trout Watersheds in Maryland" provides excellent facts about landscapes and how they matter to water temperature for healthy trout streams.
- An article in Global Change Biology by Maloney et.al., 2020 "Disentangling the Potential Effect of Land Use and Climate Change on Stream Conditions," developed a set of watershed drivers and stressors. These drivers are discussed below.
- Rice and Jastrom's study (2015) of open fields adjacent to streams suggest that a more focused analysis of water temperature trends across the Chesapeake Bay Watershed is needed. They recommend such an analysis should include the physical characteristics that could mitigate or exacerbate water temperature trends. Various landscape features that act as heaters or coolers for water temperature were summarized and correlated in their study.

To identify locations and vulnerabilities of land use change on the landscape, it is helpful to use aerial spectral imagery (high resolution 1m and 10m land use/land cover) and LiDAR to provide status and patterns of landscape change. Land use characteristics and change in the Chesapeake Bay watershed can help contextualize the nature of observed changes in impervious cover, turf grass, forests, wetlands (loss only), tree canopy, and agriculture (2021/2022). In addition, the 2013 and 2017 land use data are being incorporated into the Phase 6 Watershed Model and Chesapeake Healthy Watersheds Assessment (2021 – 2024). Other potentially useful tools are: EPA's Watershed Assessment, Tracking & Environmental Results System (WATERS) and EPA's *Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches* (2012).

C. Approach

This Element 4 Synthesis intends to characterize landscape factors influencing vulnerability and resilience to rising stream temperatures by detailing:

- landscape features that influence increases in stream water temperatures
- landscape features that moderate increases in stream water temperature
- information and tools available for use in watershed management to help with prioritizing vulnerable watersheds
- tools available to prioritize valued working lands for conservation
- landscape features that reduce the vulnerability of watersheds to stream temperature increases

Data that indicate the degree to which the various moderators affect stream temperature on a landscape scale is generally not available. Information to assess watersheds for vulnerability to climate change impacts appears to be adequate as is watershed resilience to withstand disturbances related to climate change.

The framework to be used in this synthesis is constructed from the literature referenced, along with previously applied methodologies and online decision support tools. Landscape factors and land cover characteristics that impact water temperature and related stream health measures are used as organizing features. Where applicable, research needs are identified, and potentially mitigating practices are mentioned.

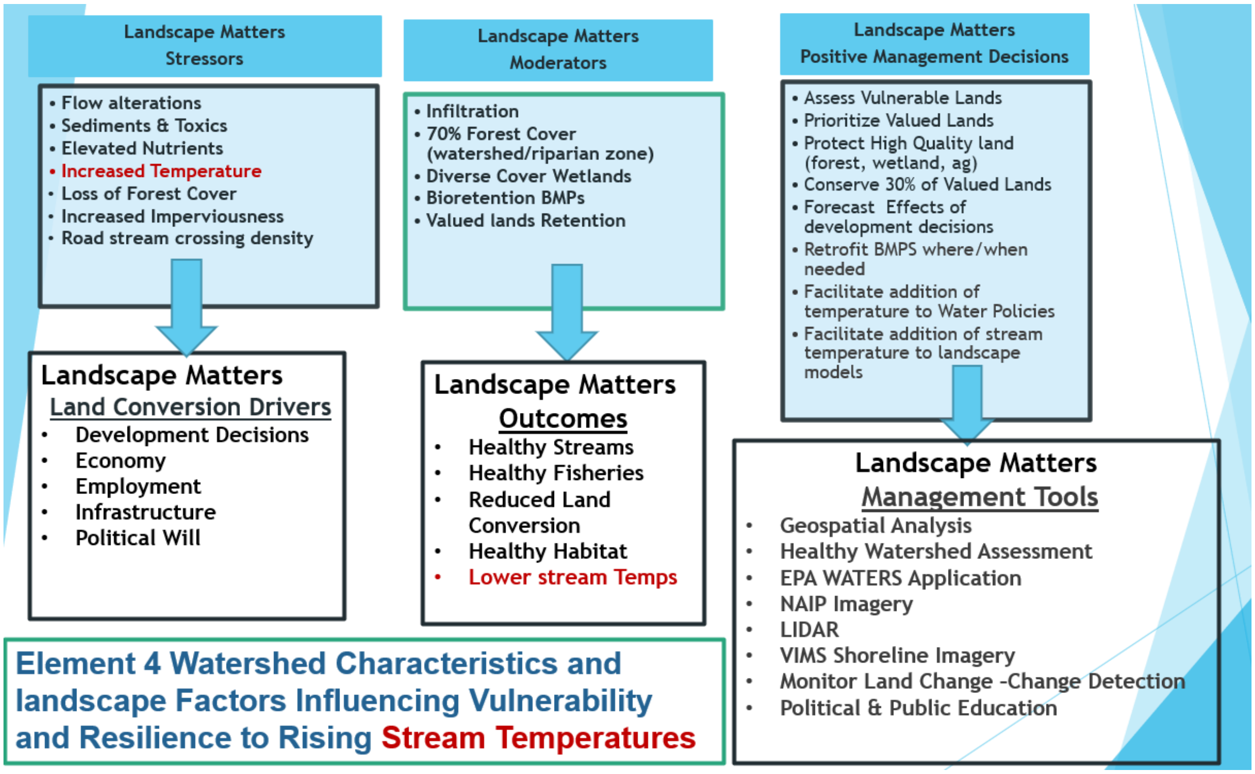
D. Synthesis

Many anthropogenic activities in the watershed have negative implications for the health of the Bay and its tributaries and can affect stream temperature. This synthesis focuses on those landscape variables that are the most influential in either directly or indirectly exacerbating or moderating stream temperature. Indicators such as biological assessments and land cover change have furthered the understanding of the deterioration of stream condition. The approach provided by the Chesapeake Healthy Watershed Assessment (CHWA) includes an index of watershed health that incorporates six key ecological attributes: landscape condition, geomorphology, habitat, water quality, hydrology, and biological condition. (Note: Water temperature is not included in the CHWA at this time but could potentially be added.)

The term 'best management practices' is used broadly in this synthesis to include anything people can do that may help to reduce stream temperatures.

Below (Figure 1) is a conceptual model developed for this Element. Each of the boxes contain aspects of landscape factors that influence watershed health. Box 1 Stressors is followed by Stressor Drivers then to Moderators (that reduce or lesson Stressors) and the benefits of the Moderators. The model goes on to feature Positive Management Decisions and tools that can be used to assist in accomplishing Management Decisions.

Figure 1: Watershed Characteristics and Landscape Factors Influencing Vulnerability and Resilience to Rising Stream Temperatures



Land Cover Effects

Land cover has a local effect on watershed health and can have a localized (e.g., shade, air temperatures) and global (e.g., carbon cycle) effect on climate. Land cover can be both moderator (e.g., forests) or stressor (e.g., developed land).

Forest Land

Forest land is decreasing in the watershed. Forests cool the air by evaporating water through their leaves and also moderate the temperature of the ground surface by shading it from direct sunlight. The evaporative cooling effect can decrease local air temperatures by several degrees Fahrenheit. The biomass of large, forested areas has a "specific heat capacity" several times higher than that of soil and air. Specific heat capacity measures the amount of heat stored or released by a unit of mass for one degree change in temperature. Finally, forest soils allow for maximum infiltration to groundwater.

Forest landscapes moderate the effect of increasing air temperature on rivers and streams with relatively narrow streams benefiting the most. Streams draining forested watersheds with major dams warmed more slowly than other watersheds and are likely to become even more important as refugia for cool-water species in a warming world (Rice and Jastram 2015).

Riparian Forest Cover is a best practice

Fisheries are well covered in Synthesis Element 2 however it bears repeating that brook trout is an exceptional indicator of both cool water and forest cover. Cold, high quality water is the basic requirement for the existence of brook trout populations (Kashiwagi, 2018). Increases in water temperatures and the lack of riparian forest cover are implicated for impacts on fisheries (Haley and Auld 2000). Note in Table 1 that the non-native brown trout is neither as sensitive to temperature or expanses of forest cover.

Table 1. *Relationship between trout and forest cover (Kashiwagi, Maryland DNR Fisheries 2018).*

Percent Forest Cover	Trout sp. present
70%	Brook Trout
52%	Brown Trout
46%	No trout

Wetlands

Wetlands with abundant vegetation are another potential cooler of water temperatures. They provide multi-dimensional surface areas for evapotranspiration leading to cooler air temperatures (Stannard et al. 2013 and Sun et al.2015). Wetlands are similar to forest cover in slowing water surges and filtering sediment and nutrients from surface run-off.

Agricultural Land

Agricultural land reduces watershed health, and some features associated with agricultural landscapes are known to impact water temperature. For example, agricultural land use may replace or reduce forested (shaded) riparian zones. Farm ponds are a known source of water warming because they are usually stagnant, shallow, and exposed to solar radiation. The exception are those ponds fed by underground springs which will be cooler than those fed by rainwater and agricultural runoff. Stream diversions such as those associated with irrigated cropland, can mean more solar exposure and therefore more heat. Irrigated cropland also allows for higher rates of evapotranspiration as water is sprayed into the air in summer (Table 2). This act can have a cooling effect on the air, and therefore the nearby water sources, but only so long as the water isn't pooling on fields, where it would be warming.

An agricultural forest buffer --even if narrow -- can have a moderating impact on water temperature. As mentioned above, this is most evident on smaller streams that benefit from the buffer's shade. Other shade-producing vegetation such as emergent wetlands and even lily pads can help reduce solar heating. But overall, agricultural lands are considered to be a source of warming water (Maryland DNR temperature TMDL studies).

Table 2 - Estimated irrigated land and water use in 2010, irrigation water withdrawals. Data adapted from Table 7 in Maupin et al. (2015). Note: These estimates include all irrigated water uses and irrigation systems, not just agricultural crop production, e.g., golf courses, parks, nurseries, cemeteries and other landscape-watering.

	Irrigated land (thousands of acres) by type				Withdrawals (in thousands of acre-feet) by source			
	Sprinkler	Micro-irrigation	Surface-water	Total	Ground-water	Surface-water	Total	Avg rate (acre-feet per acre)
Delaware	132	1.11	0	133	96.5	17.1	114	0.85
Maryland	102	3.43	0	105	59.9	20.9	80.8	0.77
NY	81.1	24.6	2.77	108	33.9	45	78.9	0.73
PA	53	15.1	0	68.1	8.28	22.1	30.4	0.45
VA	102	14.6	0	117	18	50.8	68.8	0.59
WV	2.52	0	1.09	3.61	0.06	0.04	0.1	0.03
Bay state total (whole states, not CBW-only)	473	59	4	535	217	156	373	0.70
National totals	31,600	4,610	26,200	62,400	55,400	73,900	129,000	2.07

Table 2. Estimated irrigated land and water use in 2010.

Developed Land

Developed land is increasing in the watershed. On developed and compacted land, water can be heated by both the surface and the air since it is not able to infiltrate readily. Kaushal (2012) discusses urban stream hierarchy and the loss of headwater streams to the pipes, culverts and ditches of buried streams. This alteration of hydrology (flow) goes hand in hand with increases in the transport of sediment, pollutants, toxics and impervious runoff in general, as well as increased stream temperatures. Kaushal points out that there has been an increasing appreciation for the importance of understanding the structure and function of watersheds and streams from a landscape perspective. As discussed previously, many of the landscape metrics within the CHWA mentioned thus far play a role in exacerbating or mitigating the effects of stream temperature increases and thus represent the stressors that increasing air temperatures of climate change have on streams from the coastal plains to the ridges of the Chesapeake Bay watershed.

The Patapsco River in Baltimore showed the fastest warming of any area of the Bay, implicating urbanization of the watershed and use of the Bay's waters to cool power plants along its shore. A sensitivity analysis showed that out of 14 variables, shade/transmissivity of riparian vegetation, groundwater discharge, and stream width had the greatest influence on stream temperature (LeBlanc et al 1997).

Watershed Assessments

Sets of watershed health and vulnerability metrics, some of which could be represented as stressors have been developed in the Chesapeake Bay Healthy Watershed Assessment (CHWA). Results of exploratory analyses showed that about 10 metrics were consistently selected in model iterations as significant predictors of watershed health, they are displayed in Table 3. These are related to watershed health overall and are not specific to stream temperature.

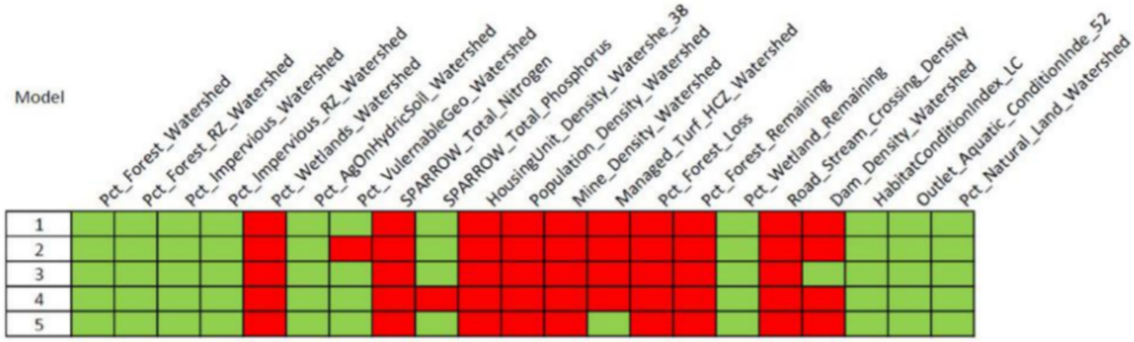


Table 3. Chesapeake Healthy Watershed Assessment Metrics- Exploratory analyses: best five model runs showing metrics selected by stepwise linear model. Green box indicates metric provided significant contribution when added to model; red indicates not significant. Note that these are metrics to assess watershed health, not stream temperature per se.

The landscape metrics in the CHWA include percent forest in the catchment, % forest in the riparian zone, Imperviousness in watershed, imperviousness in the riparian zone, agriculture on hydric soil, SPARROW total phosphorus, wetland remaining, habitat condition index, and natural land in the watershed. Noting that some of those metrics that were found to be significant are also correlated, e.g., natural land cover and forest cover. The healthy watershed outcome states that “100% of state-identified currently healthy waters and watersheds remain healthy.” There remains opportunity to better account for rising stream temperature directly through the water quality metrics in the CHWA but also assuring that other landscape factors that influence either negatively or positively stream temperature trends are refined, improved and updated regularly.

Figure 2 identifies the healthy waters, watersheds and protected lands in the Chesapeake Bay watershed. Knowing where the landscape is still intact is of great value in moving toward designating where conservation is needed to protect natural resources and their ecological services.

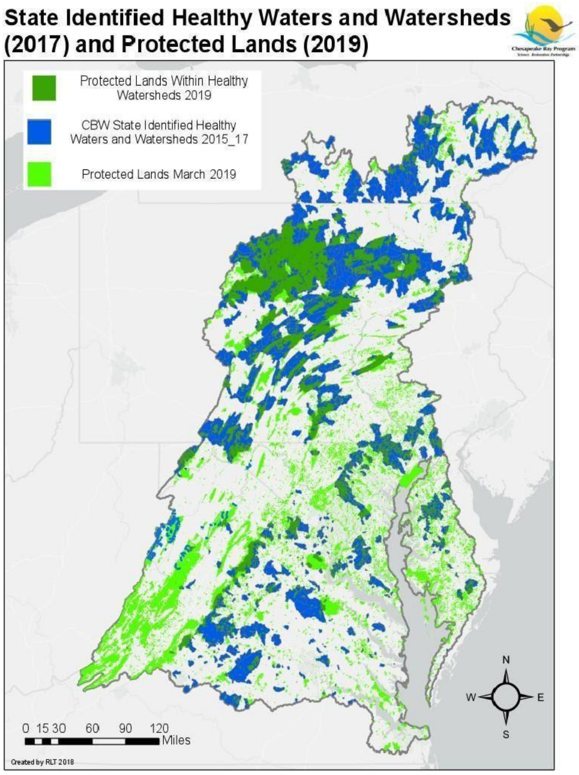


Figure 2. *State-Identified Protected Healthy Watersheds, Chesapeake Bay Program, 2019*

The degree of impact from climate change depends on the vulnerability and resilience of ecosystems and the ability to adapt to the changes. In a healthy watershed, change should not cause a permanent impact, because riparian areas and floodplains help to absorb some of the disturbance. For the purposes of the CHWA, resilience is defined by the landscape attributes and watershed characteristics that allow for high value habitat and healthy waters to sustain despite those potential stressors. CHWA includes a metric called vulnerable geology and includes areas vulnerable to surface or groundwater degradation. Values of “carbonate” and “coarse coastal plain” are considered the vulnerable areas.

The Maryland Healthy Watershed Assessment (MDHWA) pilot project has compiled candidate metrics to be tested for effectiveness (the strength of the relationship between the metric and stream response) to track watershed health in a repeatable manner (Tetra Tech, Inc., 2021). A more final listing of the key metrics --particularly stream temperature increases and moderations-- are expected in March 2022.

Like the Maryland project described above, Rice and Jastrom (2015) focused on water temperature and landscape relationships concluding that continued warming of contributing streams to Chesapeake Bay will likely result in shifts in the distribution of aquatic biota. Nelson and Palmer (2007) studied stream temperature surges in conjunction with urbanization and climate change. They found that average stream temperature increased as deforestation increased in a watershed. This finding accentuates the forest cover stream temperature relationship. This study also showed that high runoff events associated with localized rain storms caused surges in stream temperatures averaging 3.5 degrees.

Maloney et al. (2020) also produced a set of factors that influence watershed health. The study primarily used landscape elevation, stream size (smaller order streams), macro-invertebrate data (IBI, index of biotic integrity) seasonal average temperatures and land cover changes. Where land cover changes were lower, forest cover increased, and fewer streams were predicted to fall to degraded conditions (poor IBI scores). This study also presents the theory that smaller streams in valley settings are more vulnerable to degradation than those streams in the ridge elevations of the watershed. This is premised on valleys being areas of higher levels of development because of level topography making development easier.

Elements 7 & 8 Synthesis covers the many benefits forests cover and riparian buffers provide for watersheds. With advances in high resolution imagery, hydrography, modeling, monitoring and analysis, there is more understanding of how landscapes can affect stream temperature. Synthesis Element 5 has in-depth information regarding the past and current Bay conditions. This gives a good starting point for reducing impacts stressing natural resources.

Moderators and Drivers of Stressors

It is not surprising that some of the same stressors related to watershed health are also implicated in stream temperature rise. Likewise, some of the outcomes sought by the 2014 Chesapeake Bay Agreement would also benefit stream temperatures, specifically: cross-outcome goals for forestry, brook trout, land conservation, healthy watersheds, stream health, water quality, etc. Table 4 summarizes key metrics included in the Healthy Watersheds Assessment framework and how they are related to stream temperature.

Table 4. *Key metrics and relationship to stream temperature (Maryland Healthy Watershed Assessment).*

HWA Sub-Indices	Metrics	Influence on Stream Temperature
Landscape Condition	% Natural Land Cover in Watershed % Forest in Riparian Zone in Watershed % Imperviousness in Watershed	Decrease leads to elevated stream temp Decrease leads to elevated stream temp Increase leads to elevated stream temp
Hydrology	% Forest in Watershed	Decrease leads to elevated stream temp High density and low area forest cover leads to increase in stream temp

	Density Road-Stream Crossings in Watershed % Wetlands in Watershed Flow alteration score	High quality wetlands help stabilize stream temp Diverse wetlands are air temperature moderators Water withdrawal promotes high water temps
Geomorphology	Dam Density Road Density in Riparian Zone, in Watershed % Impervious in Riparian Zone in Watershed	Increase in dam density can lead to changes in land cover that may affect stream temperature, warmer temperatures are associated in closer proximity to dams (Zaidel, P., Roy A., 2021) More roads are indicators of more pavement and increased air temperatures More imperviousness in the riparian zone indicates less forest cover and warmer air temperatures.
Habitat	Nature's Network Conservation Habitats in Catchment Forest Habitat (Forest interior) MBSS Stronghold Watersheds Maryland Biodiversity Conservation Network (Bio-Net) MBSS Physical Habitat Indicator	Healthier watershed Cooler healthier environment Higher IBI scores indicate healthier watersheds Prioritizes areas for terrestrial and freshwater biodiversity conservation (sensitive habitats) Indicator of sensitive species habitat -potential conservation areas
Water Quality	Stream impairments from MD Integrated Report data Conductivity USGS SPARROW sector specific loads (manure, fertilizer, urban wastewater, atmospheric, septic) for TN, TP, sed (incremental loads) Stream Temperature (future metric for consideration 2022)	Combined report of 305(b) and 303(d) streams not meeting TMDL standard Conductivity indicates the presence of various ions related to many possible pollutants or no pollutants. Pollutants lead to higher water temperatures.(Moore et al., 2020) Can be moderated by vegetative land cover

Land Use Change	% Increase in Development in Catchment	Development can be a surrogate for imperviousness and leads to higher water temperatures.
	Recent Forest Loss in Watershed	This factor is reflected by higher air and related water temperatures
	% Protected Lands in Watershed	Increase in protected acres has potential to lower developed acres and increase more favorable land cover for moderating stream temps

The percent increase in development, the loss of forest cover, increases in imperviousness are indicated as stressors in Table 4. All of these have the common characteristics of influencing both the rate of surface runoff and the time it takes for runoff to infiltrate into local soils. One of the most important moderators of water temperature is infiltration. Water needs to get from the landscape into the streams in the most natural way possible, allowing the infiltrated water to cool. Table 5 has the infiltration rates for common landscape cover/surfaces.
In a study by Bharati et al. (2002) an established riparian buffer had infiltration rates five times that of fields or pastureland. As noted in studies cited in this synthesis, loss of forest cover is a negative factor contributing to ambient temperature increases. Those natural landscapes and best management practices that have higher infiltration rates allow for increases in groundwater recharge. Groundwater recharge is a cooling element for stream water (Murray 2006).

Table 5. Infiltration rates for common landscape cover/surfaces.

Landscape Cover	**Infiltration rate inches/hour**
Forest (pine needle cover)	15.92
Grass (avg. flat lawn)	0.28-0.88
Bioretention (Virginia DOT manual)	0.52-8.27
Rain Garden (NOAA Citizen's Guide)	0.50-2.00

This table was compiled from various guides, papers, and websites (Okay 2021)

Geospatial analysis tools can be used to forecast development decisions which could impact water temperature. StreamCat (Catchments) is an extensive database of landscape metrics for ~2.65 million stream segments within the continental United States and one of the only assessments that includes stream temperature.

Next Steps

1. Work to integrate stream temperature data and other landscape stressor and moderator information into assessments and priority mapping and analysis
    - Add stream temperature to Water Quality metrics of the Chesapeake Healthy Watersheds Assessment

- Investigate opportunities to better integrate stream temperature considerations into Chesapeake Conservation Partnership priority conservation atlas mapping efforts.
- Investigate opportunities to connect watershed health, vital lands and habitat protection to stream temperature and water quality goals

2. Work to decrease stressors
   - Emphasize the need to maintain natural landscapes (especially forests and wetlands) and healthy watersheds
   - Continue to improve policies that keep these land covers protective of water temperature
   - Continue to promote permanent protection of these lands

3. Employ practices that modify stream temperatures
   - Promote best practices for cooling streams as listed in Table 4. (Note that Synthesis for Element 7/8 goes into greater depth on best management practices).

E. Evaluation Element 4 Synthesis

In considering research that would be used in this Synthesis the overarching qualifications were: The research originated in, is related to, or can be applied to the Chesapeake Bay Watershed. To characterize the landscape/land use issues that relate to disturbances or stress to watersheds, a suite of assessment tools was highlighted and the metrics used for assessment are described and represented in tabular form. Stressors common to the assessment tool metrics and supported by the science of the research papers are:

- Land use changes/conversions (especially loss of forest cover, increase of impervious surface)
- alteration of stream flow
- increased sediment
- toxics
- pollutants and nutrients.

The objective is to show that these watershed stressors are causative factors to increased stream water temperatures.

- Nelson and Palmer (2007) related a stream temperature increase of 3.5 degrees C in response to high surface runoff events and deforestation.
- Maloney et.al (2020) demonstrated that with increased impervious cover stream conditions declined and with increased tree canopy conditions improved.
- Kaushal (2012) had findings that agree with those of Maloney.
- Kawishagi (2018) linked percent forest cover to the presence of trout in Maryland cold water streams.
- Goetz (2003) showed a positive relationship between forest buffers and stream health.

- Stannard et al. (2013) and Sun et al.(2015) suggested wetland restoration as a tool to reduce air temperature increases stemming from climate change.

Alteration of stream flow and stream temperature fluctuations were addressed by linking infiltration of surface water into the soil to recharge groundwater. The discharge of the water from groundwater can have a cooling effect that stabilizes stream temperature, and it also stabilizes seasonal flows, depending on other key landscape factors. These are important factors for cool water fisheries. The relationship of infiltration with various types of land cover is highlighted. Forests have the highest infiltration rates. As a land cover they facilitate infiltration to groundwater better than other land cover. In contrast, pavement has the highest run-off coefficient limiting infiltration and groundwater recharge. How quickly water runs off determines the concentration time which allows the water to infiltrate into the soil and recharge groundwater. The infiltration rates are lower for the more impervious cover types and higher for the more porous cover types.

The presentation is strong on tools, moderate on scientific support to identify stressors and moderators. Data that indicate the degree to which the various moderators affect stream temperature on a landscape scale is generally not yet available. Watershed assessment, vital lands and habitat priority mapping and other related living resource mapping and assessments should be evaluated to include more robust information on stream temperature as it is related to watershed health, water quality, landscape resilience, and high value habitat. Information to assess watersheds for vulnerability to climate change impacts appears to be adequate as is watershed resilience to withstand disturbances related to climate change.

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